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A Model for Designing Planar Magnetron Cathodes

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Lawrence Livermore National Laboratory

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Planar magnetron cathodes have arching magnetic field lines which concentrate plasma density to enhance ion bombardment and sputtering. Typical parameters are: helium at 1 to 300 milli-torr, 200 to 2000 gauss at the cathode, 200 to 800 volts, and plasma density decreasing by up to ten times within 2 to 10 cm from the cathode. A 2D, quasineutral, fluid model yields formulas for the plasma density: n(x,y), current densities: $\mathbf{j}(x,y)$, $\mathbf{j}_e(x,y)$, $\mathbf{j}_+(x,y)$, the electric field: $E_y(y)$, and the voltage between the cathode surface and a distant plasma. An ion sheath develops between the cathode and the quasineutral flow. The thickness of this sheath depends on processes in the quasineutral flow. Experiments shows that T_e (3 -> 8 eV) adjusts to ensure that $\alpha_0\tau \approx 2.5$ in helium, for ionization rate α_0 (10^4 -> 10^5 s^{-1}), and electron transit time to the unmagnetized plasma τ (10 -> 100 μs). Helium glow discharge cathode fall $\alpha_0\tau$ is about 2.5, though this occurs at much higher voltage.

This work was performed under the auspices of the U.S. DOE by LLNL under contract no. W-7405-Eng-48.

Introduction

This report outlines an analytical model of the distribution of plasma in the cathode fall of a planar magnetron cathode. Here I continue commentary on previous work, and introduce an ion sheath model to describe the discharge “dark space” below the magnetron halo. Figure 1 is a schematic of these magnetized cathode falls. A constant density ion sheath extends from the cathode surface to a distance y_* of the order of millimeters. The bulk of the cathode fall is the quasi-neutral region with falling density extending to a distance y_0 of the order of centimeters. Beyond y_0 the plasma electrons are no longer magnetized, and the plasma is uniform.

Quasi-neutral flow

The original problem prompting my work was to find the spatial distribution of plasma, and the voltage drop, as a function of arbitrary magnetic field $\mathbf{B}(x,y) = \mathbf{B_x}(x,y) + \mathbf{B_y}(x,y)$, where x is parallel to the cathode and y is perpendicular. Planar magnetron cathodes were being used to lower the impedance of a discharge device designed for an application other than as a sputtering source. The purpose of the model was to facilitate this engineering. Reference 1 describes the quasi-neutral fluid model of the magnetized cathode fall. Below is a summary of those results.

Summary of Analytical Results

Equations from reference 1 are shown in the logical sequence for any specific calculation. The equations are numbered exactly as in reference 1 (please see that report for a complete description).

$$v_e^2 = \frac{\dfrac{5kT_e}{m_e}}{2\dfrac{\nu_{eN}}{\alpha_0} - 1} = \left(\frac{j_\infty}{en_\infty}\right)^2 \qquad (56)$$

$$\frac{v_{ez}}{v_{ey}} = \mu_e B_x \qquad v_{ey} = \frac{v_e}{\sqrt{1 + \mu_e^2 B_x^2}} \qquad v_{ez} = \frac{v_e \mu_e B_x}{\sqrt{1 + \mu_e^2 B_x^2}} \qquad (50)$$

$$\mu_e B_x(0,y_\infty) \;=\; 1 \tag{53}$$

$$F(y) \;=\; \int_0^y \frac{\alpha_0}{v_{ey}(0,\eta)}\, e^{\int_y^\eta \frac{\alpha_0}{v_{ey}(0,\xi)} d\xi}\, d\eta \tag{52}$$

$$u_e \;\equiv\; \frac{5kT_e}{2e} + \frac{mv_e^2}{2e} \tag{37}$$

$$\phi_\infty \;=\; u_e\left(\frac{1}{1 - F(y_\infty)} \;-\; 1\right) \tag{54}$$

$$\phi(y) \;=\; (u_e + \phi_\infty)F(y) \tag{52}$$

$$\frac{d\phi}{dy} \;=\; \frac{\alpha_0(u_e + \phi_\infty)}{v_{ey}(0,y)}(1 - F(y)) \quad = \; -E_y \tag{52}$$

$$v_+^2 \;=\; \frac{2e}{m_+}(\phi_\infty - \phi) \tag{40}$$

$$n(x,y) \;\equiv\; n_0(y)\; L(x,y) \qquad\qquad n_0(y) \;\equiv\; n(-x_p,y) \tag{59}$$

$$n(x,y) \;=\; n(-x_p,y)\; \exp\left[\, \frac{v_e}{D_e - D_+} \int_{-x_p}^{x} \frac{\mu_e^2 B_x B_y}{\sqrt{1 + \mu_e^2 B_x^2}}\, dx \,\right] \tag{58}$$

$$a(y) \;\equiv\; \Delta z\; e(D_e - \; D_+) \int_{-x_p}^{+x_p} L(x,y)\; dx \tag{64}$$

$$b(y) \;\equiv\; \Delta z\; e \int_{-x_p}^{+x_p} [\; L\cdot(\mu_e E_y + \frac{v_{ez}^2}{v_{ey}}) \;+\; (D_e - D_+)\frac{\partial L}{\partial y} \,]\; dx \tag{65}$$

$$H(y) \;\equiv\; b(y)/a(y) \qquad\qquad K(y) \;\equiv\; I_0/a(y) \tag{66}$$

$$n_0(0) = n_\infty e^{\int_0^{y_\infty} H(\eta)\, d\eta} - \int_0^{y_\infty} K(\eta)\cdot e^{\int_0^{\eta} H(\xi)\, d\xi}\, d\eta \qquad (67)$$

$$n_0(y) = e^{-\int_0^{y} H(\eta)\, d\eta}\cdot[n_0(0) + \int_0^{y} K(\eta)\cdot e^{\int_0^{\eta} H(\xi)\, d\xi}\, d\eta] \qquad (67)$$

$$I_M = \int_0^{y_\infty}\int_{-x_p}^{+x_p} -e\, n(x,y)\, v_{ez}(x,y)\, dx\, dy \qquad (68)$$

Besides the magnetic field, the model requires T_e, j_∞ or n_∞, and both α_0 and ν_{eN} (which depend on T_e and the gas). The proper T_e to select for any gas mixture is that which gives the same $\alpha_0\tau$ as a glow discharge conveying the same amount of current. Please see reference 2 for a complete discussion on how $\alpha_0\tau$, the product of the ionization rate and electron transit time from the cathode to y_0, allows for a direct comparison of cathode falls from planar magnetron cathodes and glow discharges. Magnetized cathodes operate at lower voltage than glow discharges of equal current because electrons are confined near the cathode for a longer time thus producing the required ionization at lower average energy.

After reference 1 was issued I realized that equation (52) can be stated more simply as:

$$F(y) = 1 - \exp\left(-\int_0^{y} \frac{\alpha_0}{v_{ey}(0,\eta)}\, d\eta\right) \qquad (52a)$$

In practice the lateral limits $\pm x_p$ should be taken beyond the poles of the flanking magnets (more generally, beyond the points where $B_x(x,0) = 0$ given that $x = 0$ is the center of the magnetron track and halo). These limits appear in equations (59), (58), (64), (65), (68). Both references 1 and

2 show examples of spatial distributions of density and current calculated from these equations.

Selecting an Ion Sheath

Electrons near the cathode surface are immobilized by $B_x(x,y)$, and an ion sheath forms. Define a Debye length based on ion kinetic energy, V_i in eV:

$$h_{D_i} = \sqrt{\frac{\varepsilon_0 V_i}{e\ n}} \tag{1}$$

The sheath forms to a distance y from the cathode, where the local density n(y) and voltage V(y) (which sets V_i) make $h_{Di} = y$. The ion kinetic energy is estimated most simply as $V_i = V_0 - V(y)$, for V_0 = the total voltage drop between the cathode and the end of the magnetized "fall" at y_0 [same as y_∞ in reference 1, defined by equation (53)]. V(y) rises from zero at the cathode to V_0 at $y = y_0$. ∴

$$h_{D_i} = \sqrt{\frac{\varepsilon_0 (V_0 - V(y))}{e\ n(y)}} = y \tag{2}$$

It is assumed here that only the most dense plasma, between the magnet poles (x=0), need be considered. Equation (2) is an energy condition for sheath formation: ions must have sufficient kinetic energy to create a charge separation of density n over a distance y with electrons immobilized by B_x.

A unique value of y is determined with the addition of a current conservation condition: (ion current from the sheath) = (ion + electron currents from the quasi-neutral flow):

$$I_h = I_+ + I_e$$

$$\Delta Z \int_{<\text{pole}(-)}^{>\text{pole}(+)} e\ n_h(x,0)\ v_h\ dx = \Delta Z \int_{<\text{pole}(-)}^{>\text{pole}(+)} e\ n(x,y_*)\ [v_+ + v_e]\ dx$$

Assuming that most of the current is conveyed at x = 0 (between poles), then the integration over x can be dropped (ΔZ = length of magnetron track), leaving:

$$e\, n_h(0)\, v_h \;=\; e\, n(y_*)\, (v_+ + v_e)$$

The ion density in the sheath is constant as no ionization occurs because the electrons are immobilized, $\therefore$ $n_h = n(y_*)$ = the plasma density at the interface between the sheath and the quasi-neutral flow. All the current at the cathode surface is carried by ions at $V_i = V_0$, [recall that $V(y{=}0) = 0$], the ions being accelerated through the sheath. Thus the current continuity expression above is simplified to:

$$v_h \;=\; \sqrt{\frac{2\,e\,V_0}{m_+}} \;=\; \sqrt{\frac{2\,e}{m_+}(V_0 - V(y_*))} \;+\; v_e(y_*) \qquad (3)$$

Here $v_e(y)$ is the fluid velocity component in the +y direction.

Now solve for y_* by eliminating $V_0 - V(y)$ from both (2) and (3). The first and then last steps of this algebra are as follows:

$$\sqrt{\frac{2\,e\,V_0}{m_+}} \;=\; \sqrt{\frac{2\,e}{m_+}\left(y_*^2\,\frac{e\,n(y_*)}{\varepsilon_0}\right)} \;+\; v_e(y_*)$$

$$y_* \;=\; \sqrt{\frac{\varepsilon_0\,m_+}{2\,e^2\,n(y_*)}}\left(\sqrt{\frac{2\,e\,V_0}{m_+}} \;-\; v_e(y_*)\right) \qquad (4)$$

The sheath starts where quasi-neutral $n(y)$ and $v_e(y)$ are related to coordinate y as in equation (4). In this work a simple splice is effected: below y_* is ion sheath, above y_* is quasi-neutral flow. This formula produces a sheath height comparable to the “dark spaces” seen in the experiment. Note that for negligible $v_e(y_*)$, the expression for y_* reduces to a Debye length formula:

$$y_* \;=\; \sqrt{\frac{\varepsilon_0\;V_0}{e\,n(y_*)}}$$

reflecting formula (1) with specific choices for ion kinetic energy and sheath density. These choices are determined by the balance of ionization and transport in the magnetized, quasi-neutral flow.

Reference 3 discusses ion sheaths with magnetized electrons, however the regime of interest in that report was very different than that of sputter discharges. The essential point here is that ions can use their kinetic energy to create a charge separation when electrons are fixed by transverse field lines. The relationship between the ion energy, the charge density and the extent of the separation is the Debye length formula.

Magnet orientation

Figures 2, 3, and 4 show the types of magnet orientations discussed in reference 2. A magnet whose polar axis is perpendicular to the cathode surface nearest the plasma halo is said to be at 0°. A magnet whose polar axis is parallel to the cathode surface closest to the plasma halo is said to be at 90°. A fin cathode as shown in Figure 4 was found to produce the lowest overall discharge impedance in the experiments described in reference 2.

References

1) "A 2D Fluid Model of the DC Planar Magnetron Cathode," UCRL-ID-122494, 15 November 1995

2) "Comparing a 2D Fluid Model of the DC Planar Magnetron Cathode to Experiments," UCRL-ID-125434, 15 May 1996

3) "Electric Vortex in MHD Flow," UCRL-ID-121162, 1 May 1995

The above are available at:

http://www.llnl.gov/tid/lof/lof_home.html

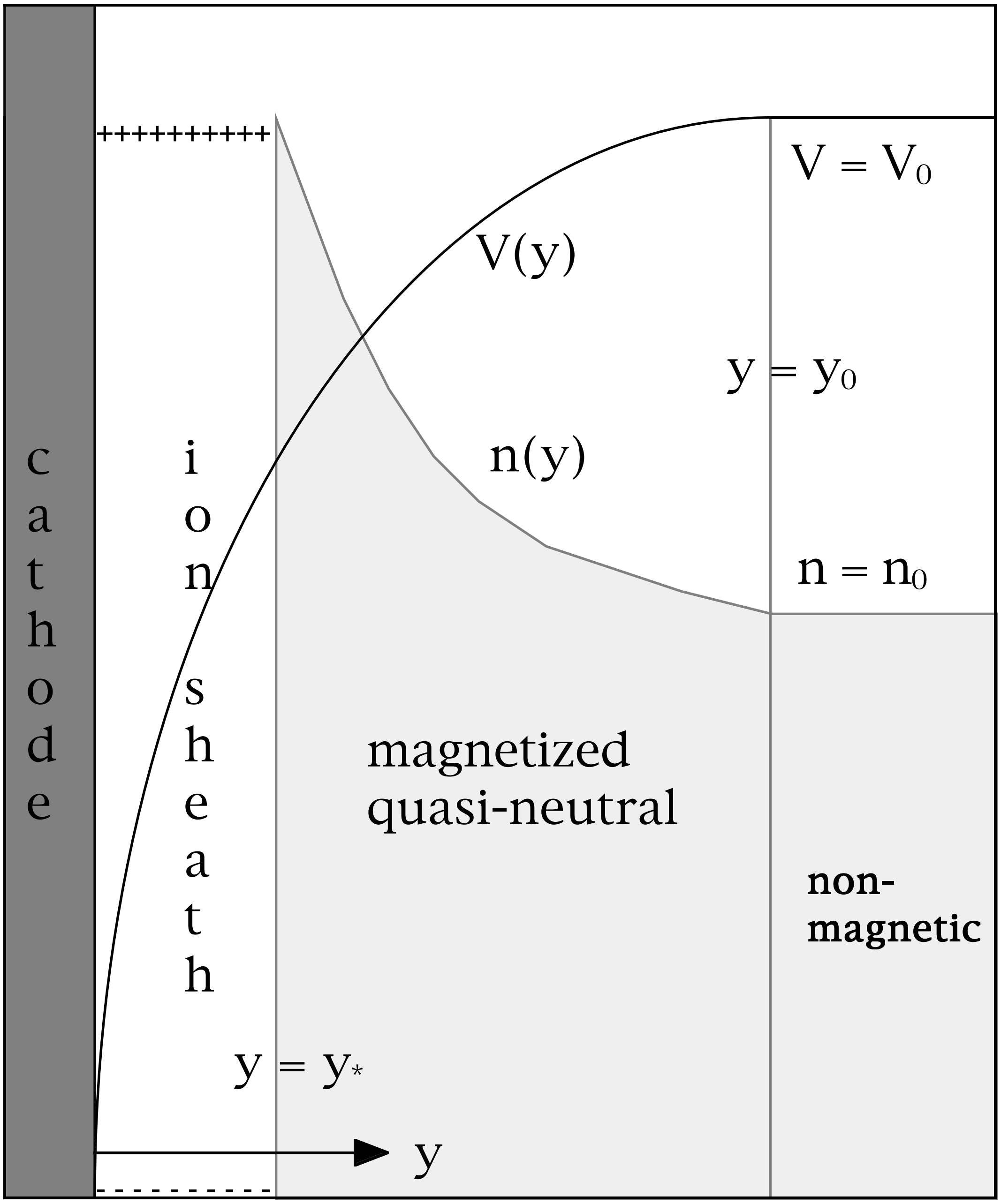
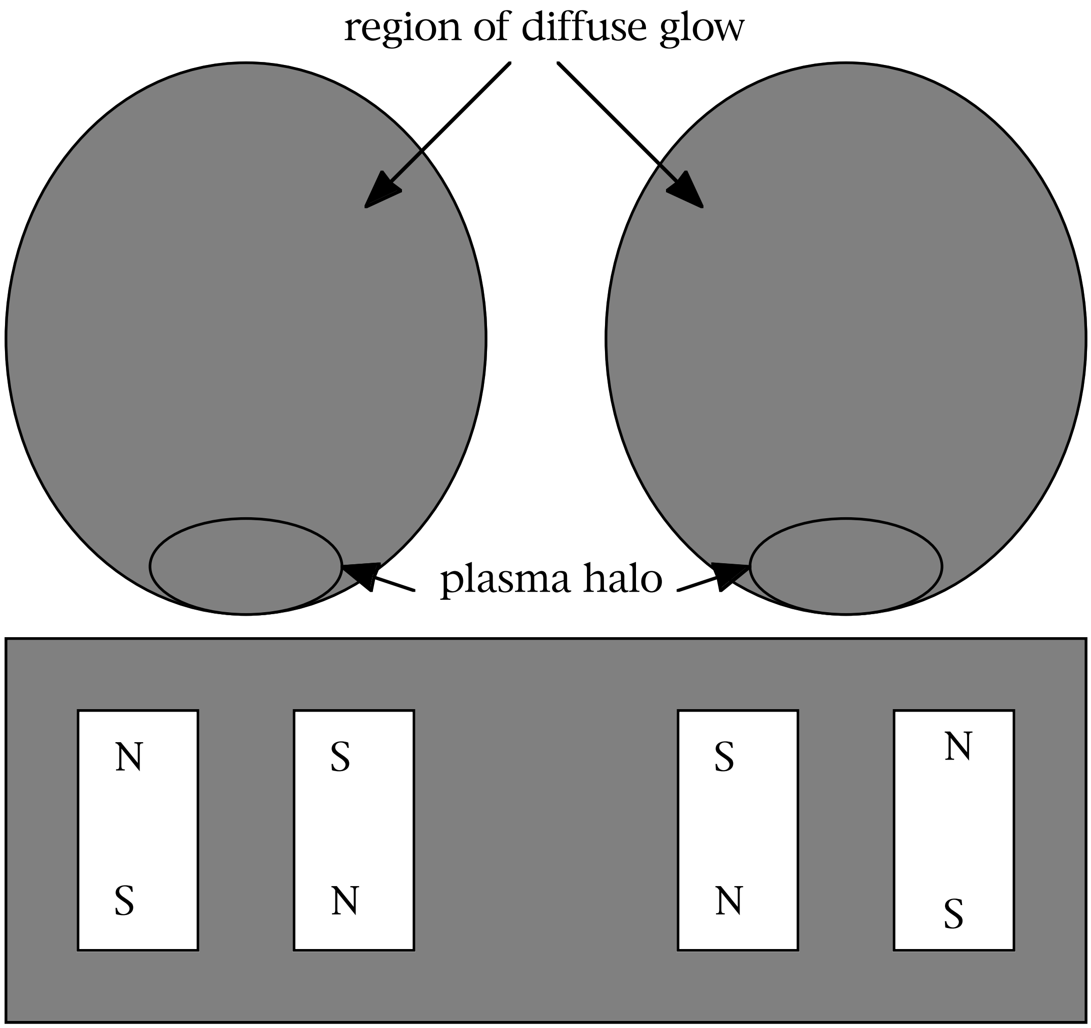


Figure 1: schematic profile of planar magnetron cathode fall



Cross section of a cathode with magnets @ 0°

Figure 2: 0° cathode

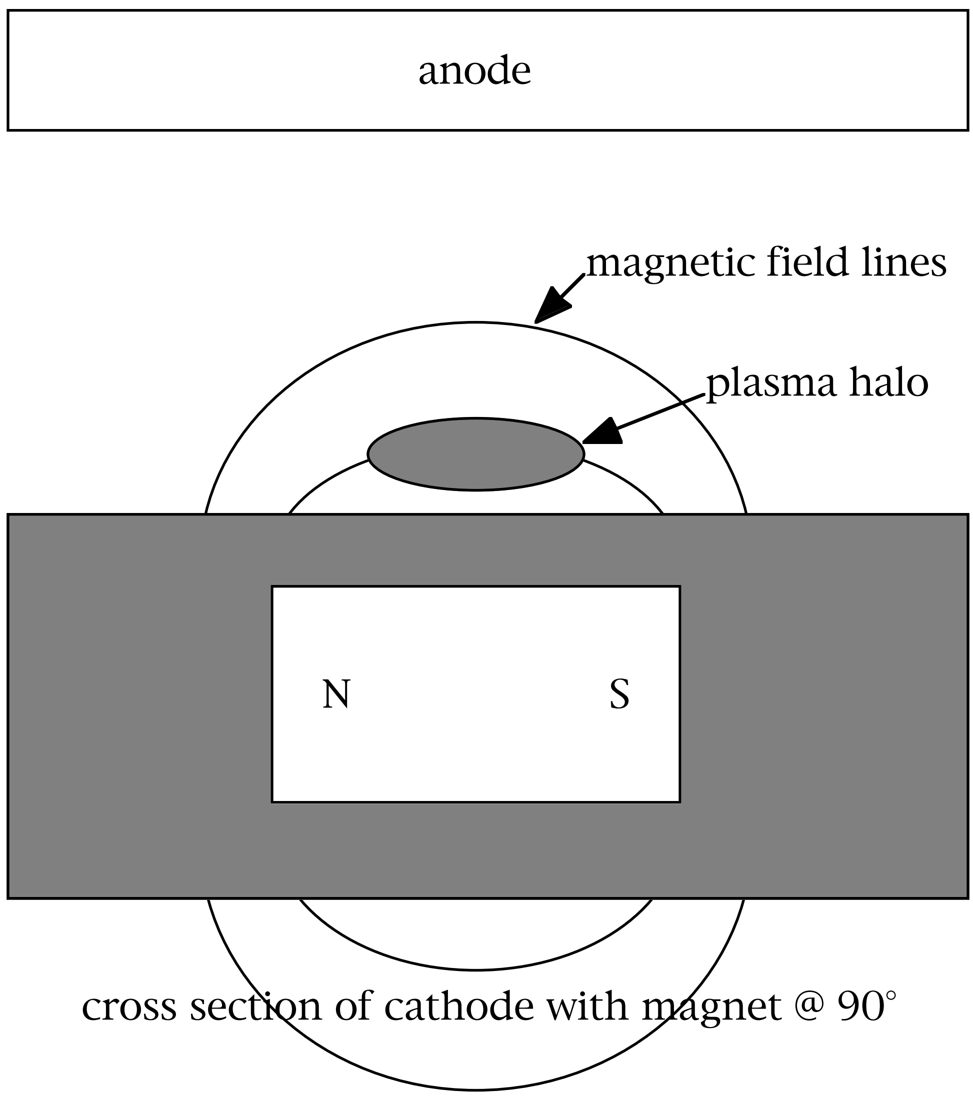
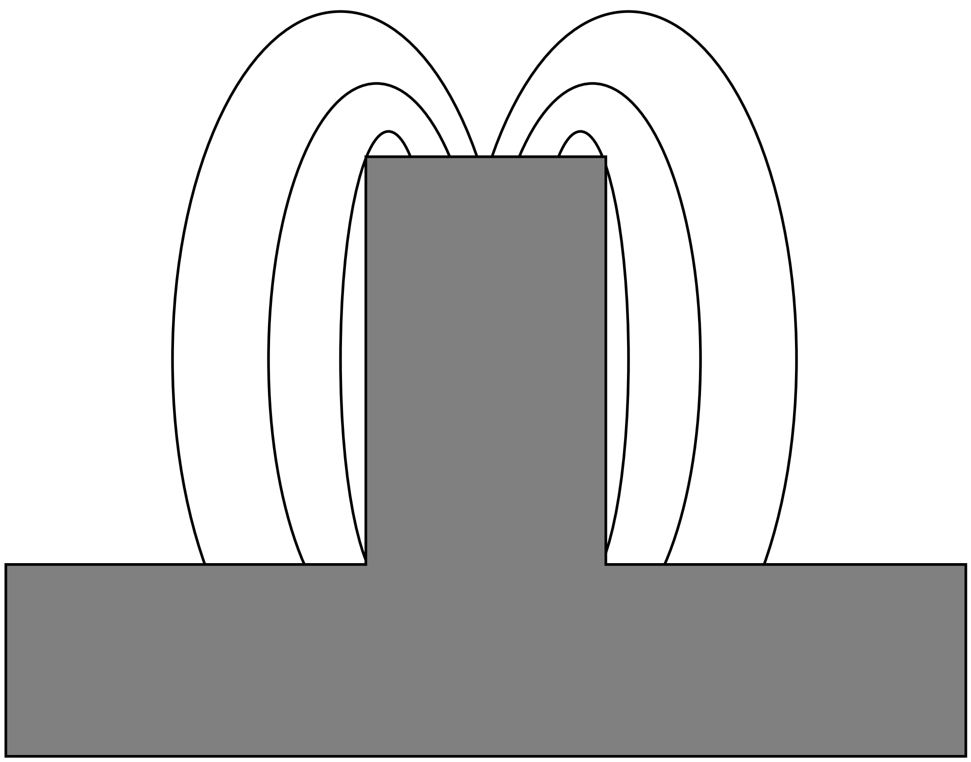
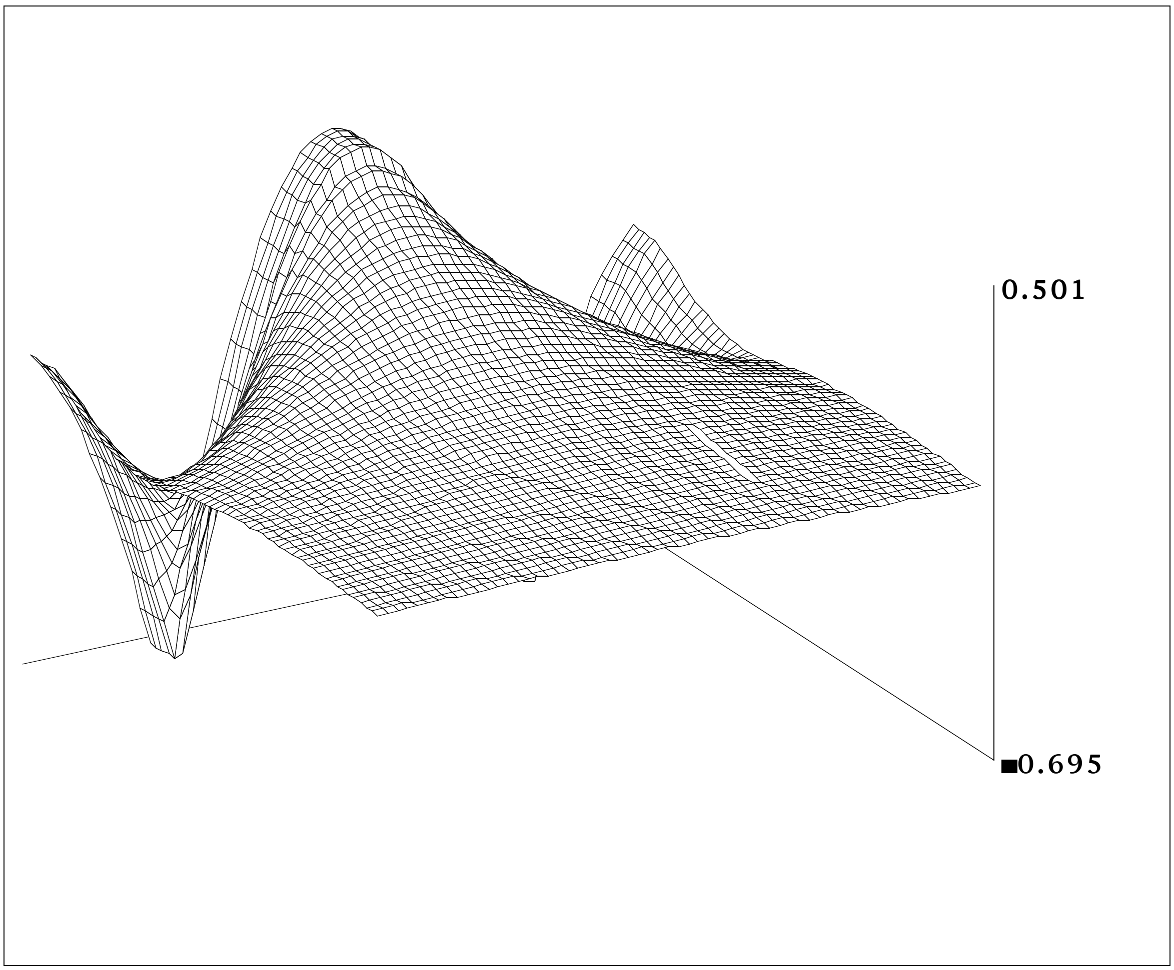


Figure 3: 90° cathode



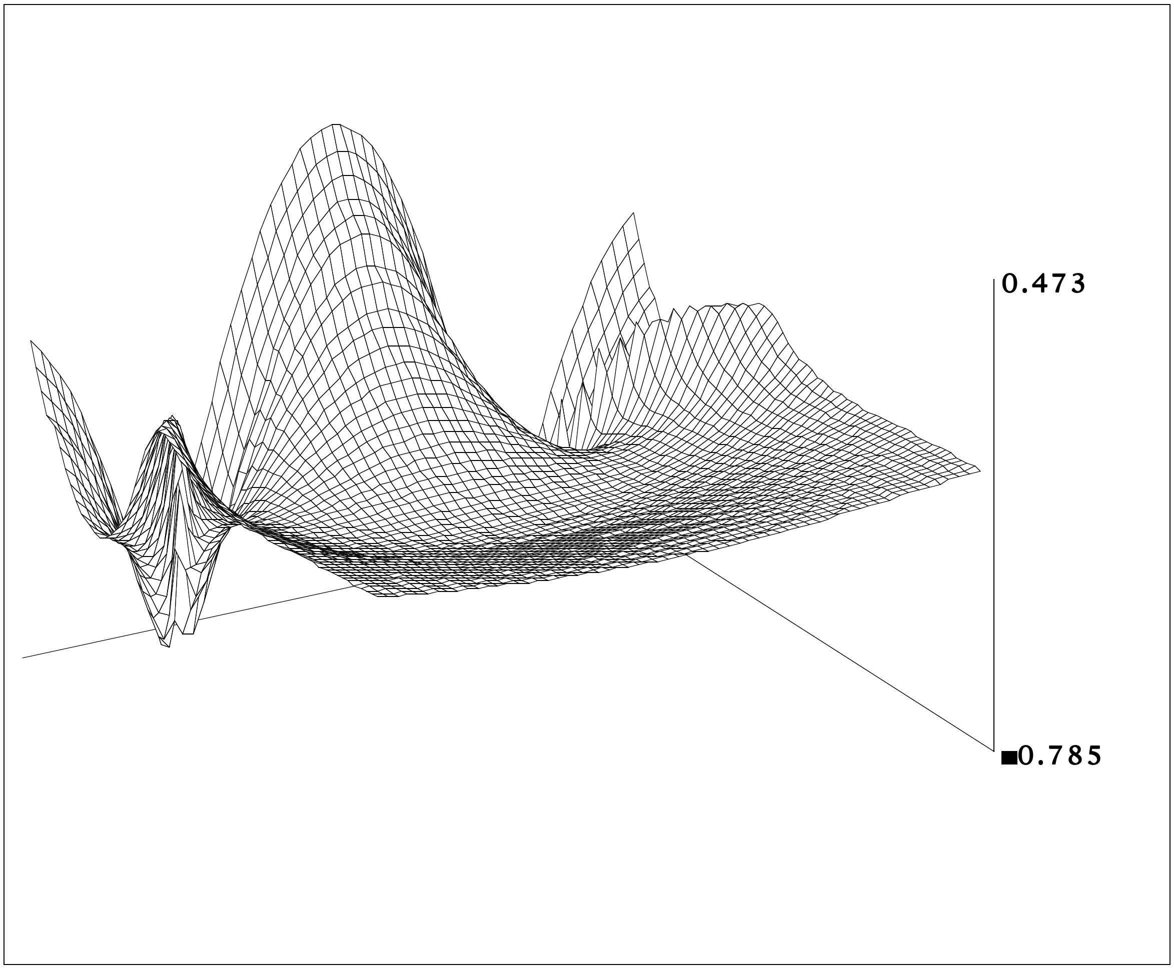


Ln_i

normalized ion density (log)

$$n_0 = 3.089 \cdot 10^{14}$$

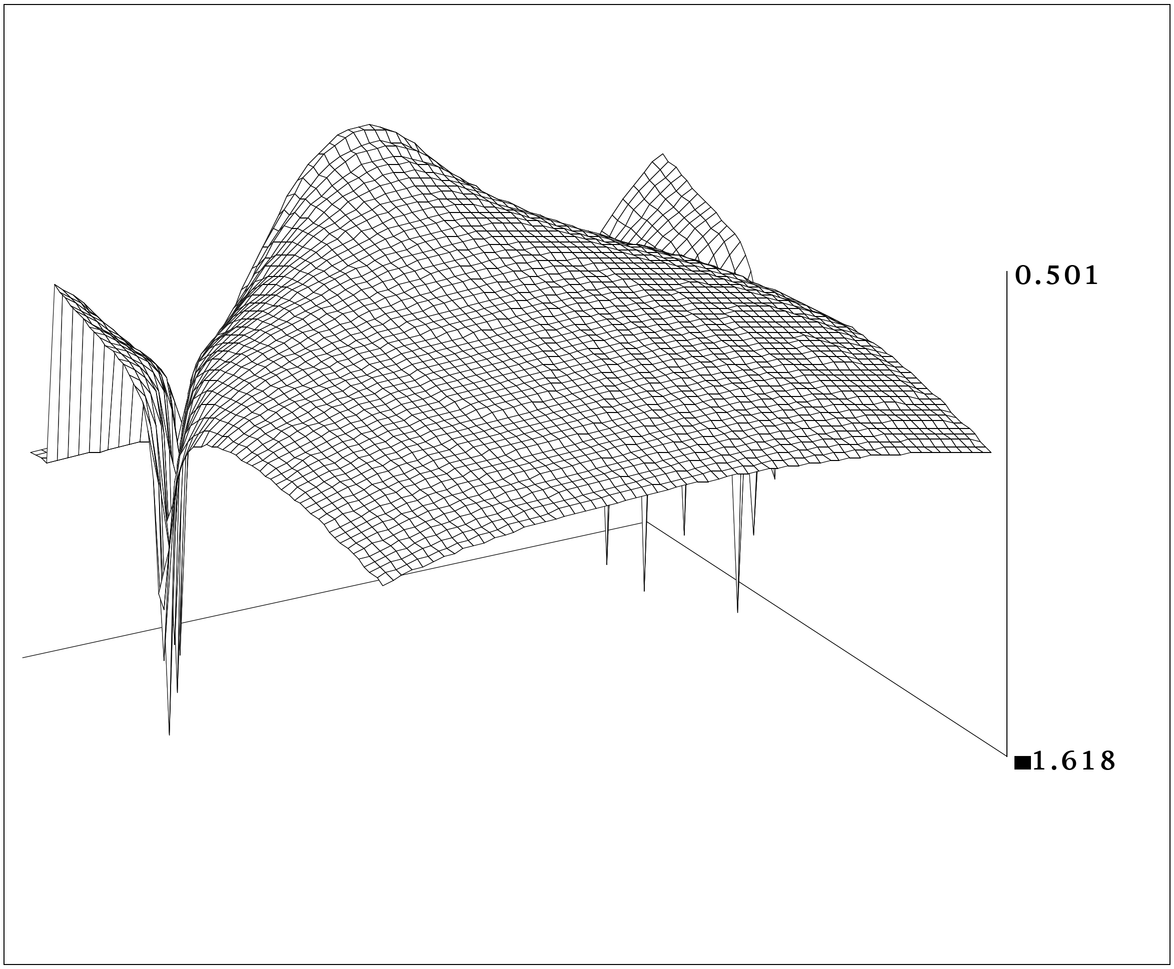
normalization density, m^-3



normalized conduction current density (log)

$j_0 = 5.114$

normalization current density, amps/m^2

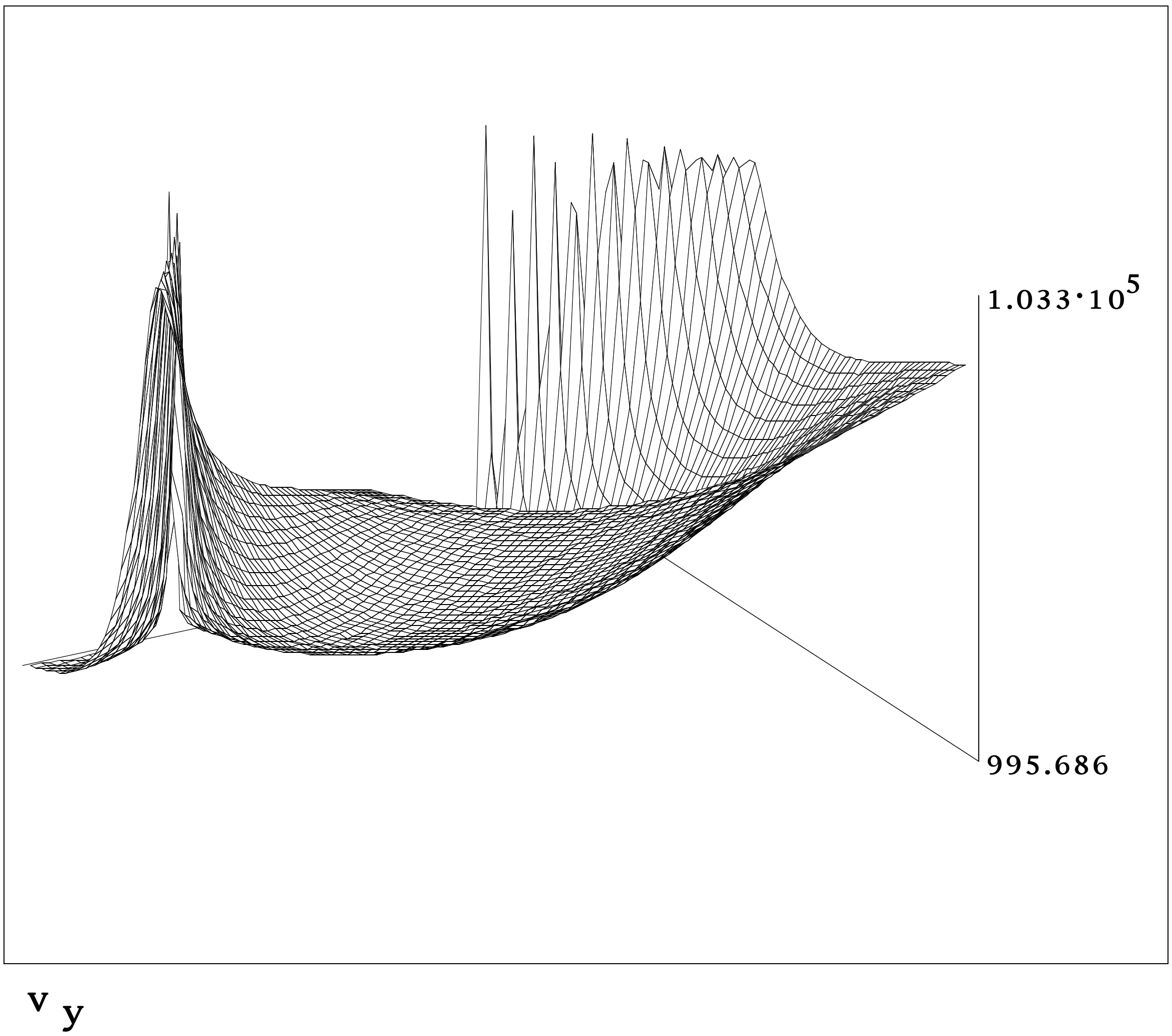


$L j_z$

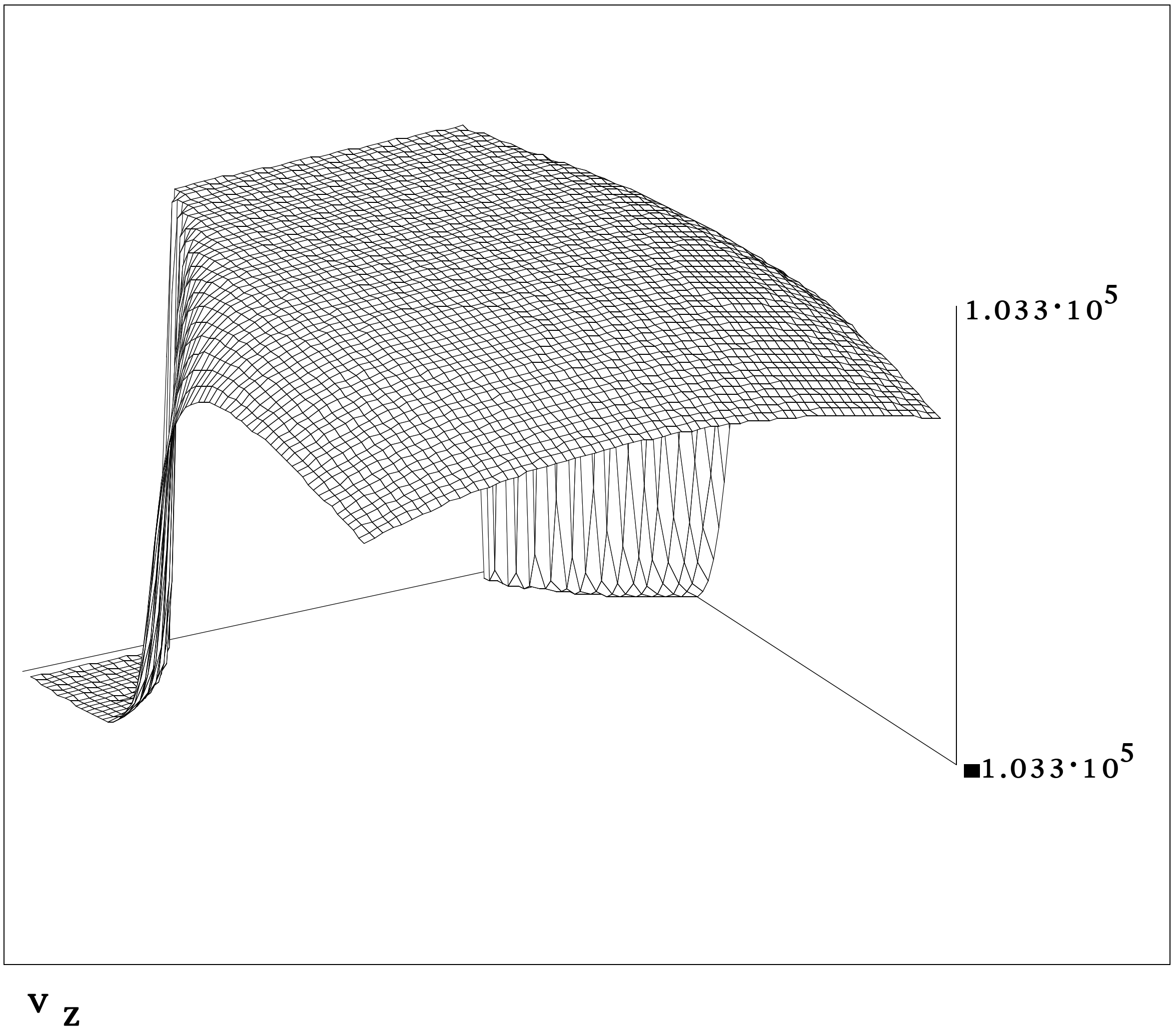
| normalized magnetron current density |, (log)

$j_0 = 5.114$

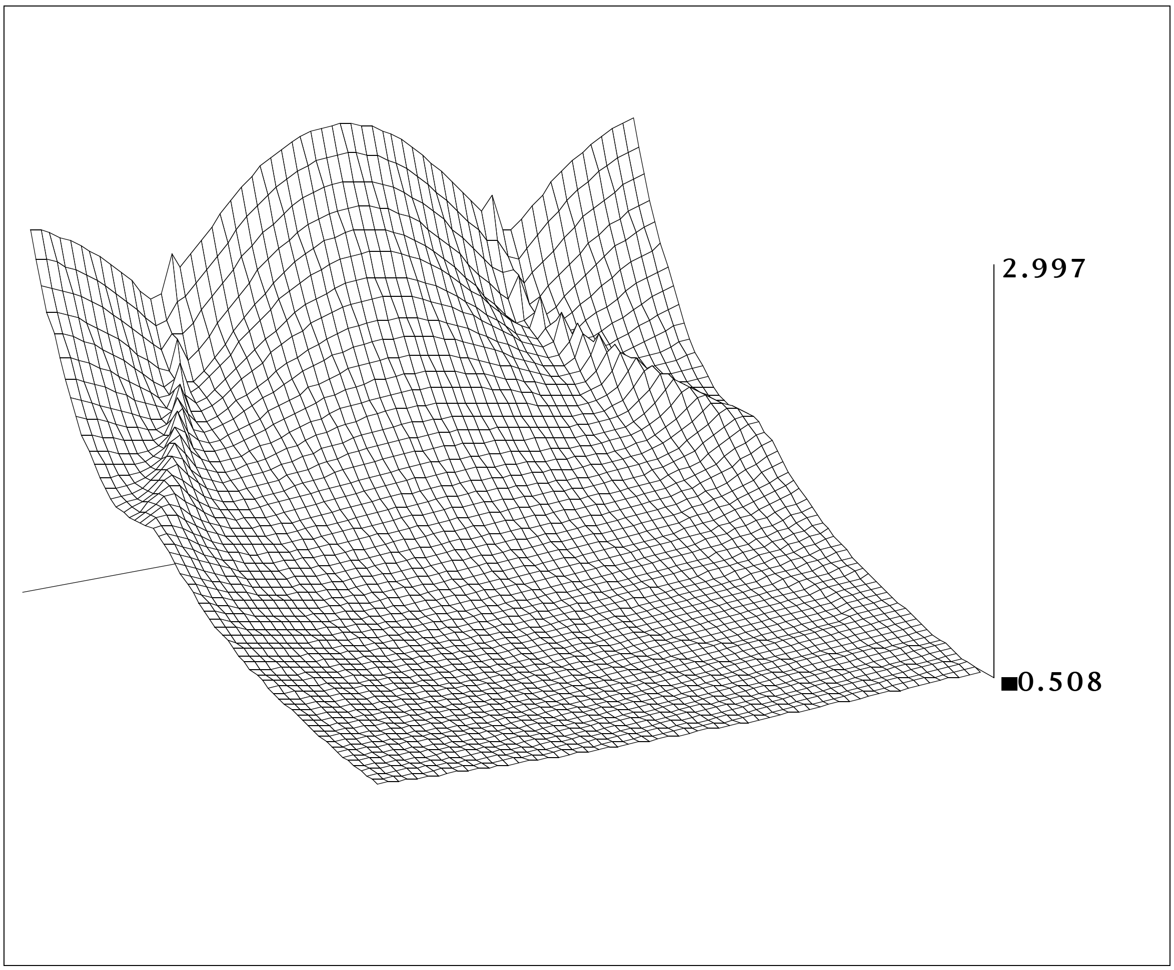
normalization current density, amps/m^2



electron velocity (conduction), m/s



electron velocity (magnetron), m/s

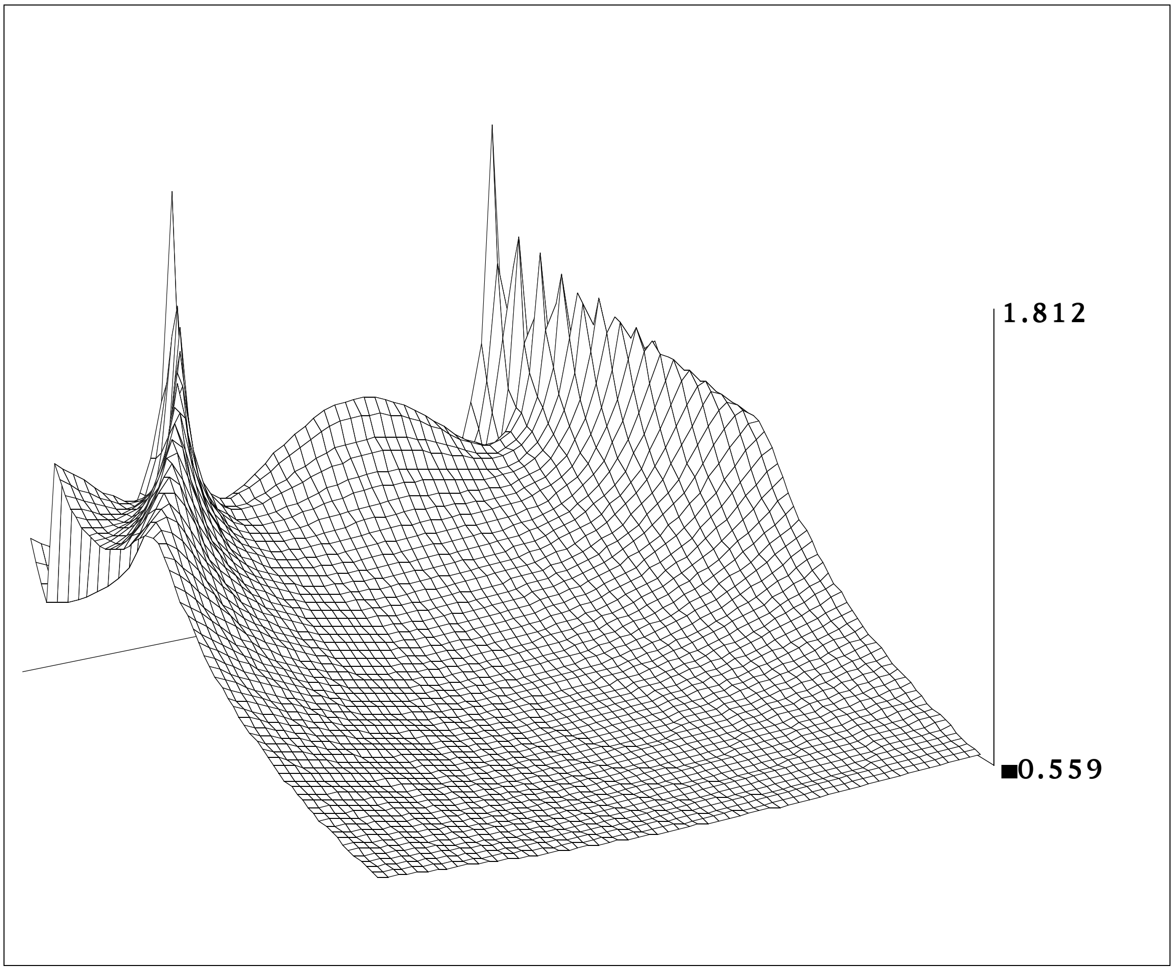


LQ

normalized power density (log)

$$Q_0 = 988.065$$

normalization power density, Watts/m^3

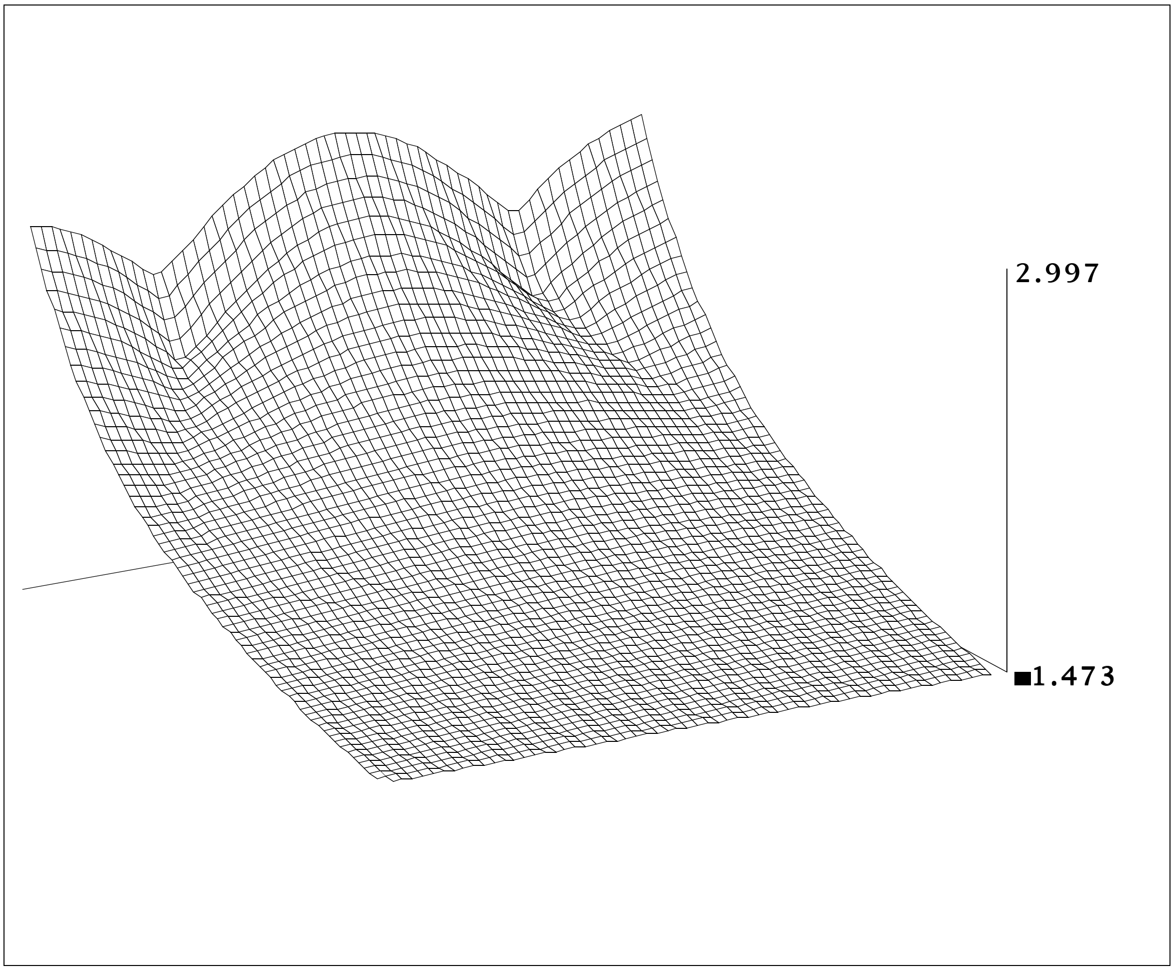


LQ_e

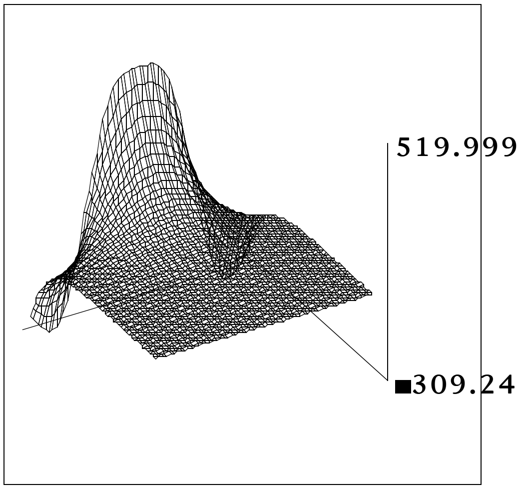
normalized electron power density (log)

$$Q_0 = 988.065$$

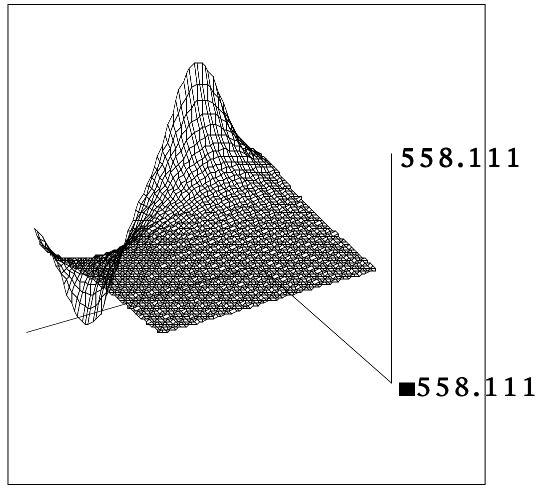
normalization power density, Watts/m^3


2.997
1.473

Magnetic field components x: transverse, y: perpendicular

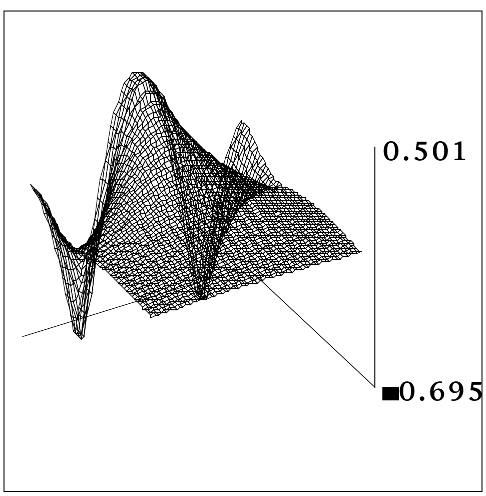


$HX \cdot 10^4$

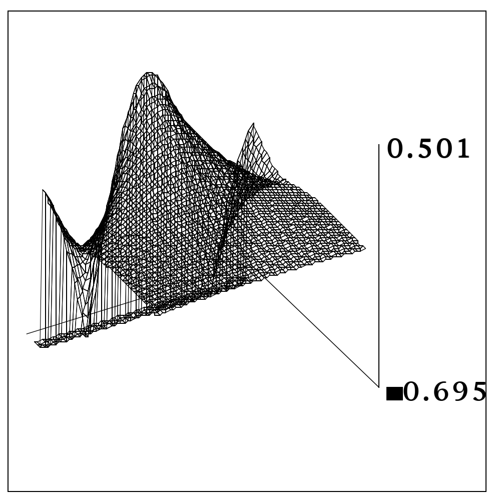


$HY \cdot 10^4$

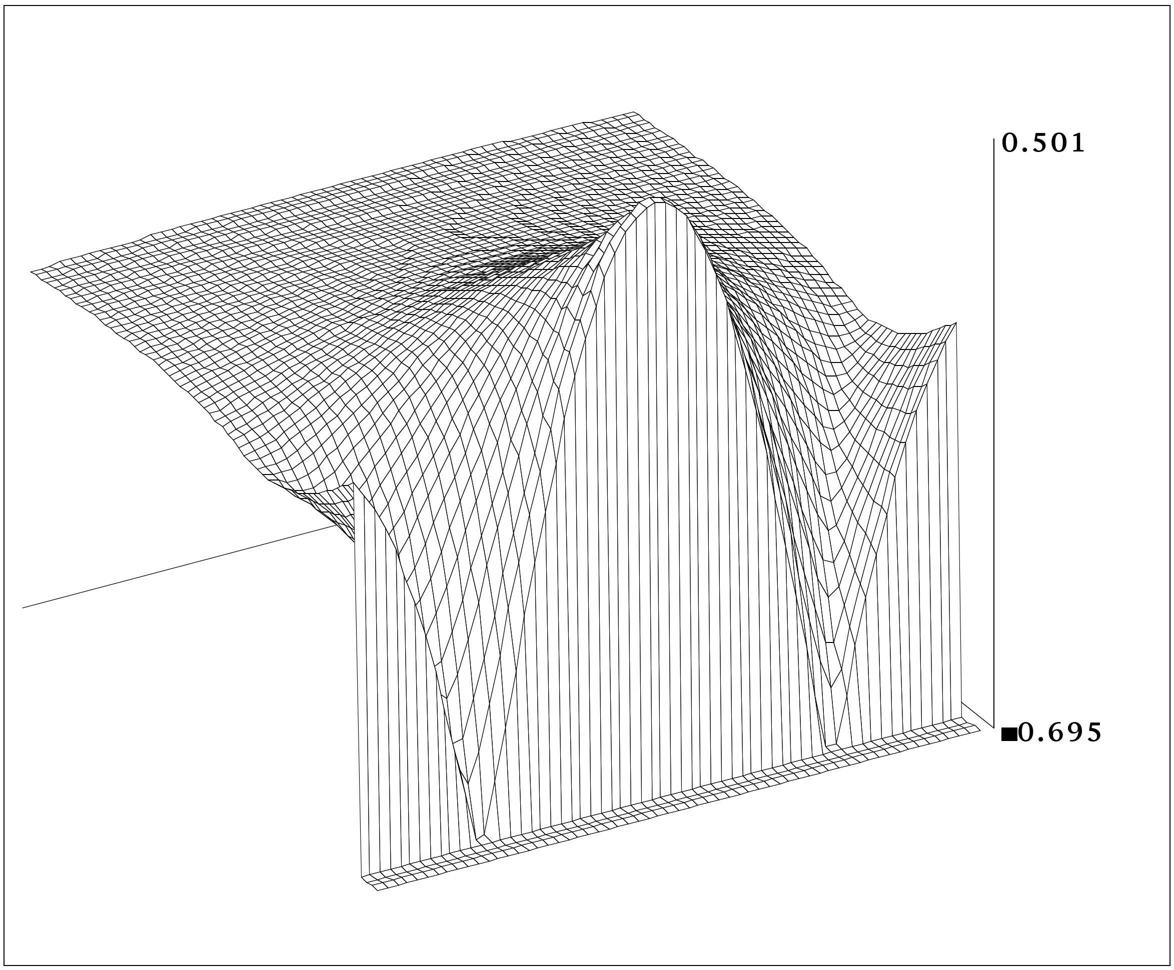
Log density ratios: ions & electrons; ion sheath near cathode



Ln_i



Ln_e

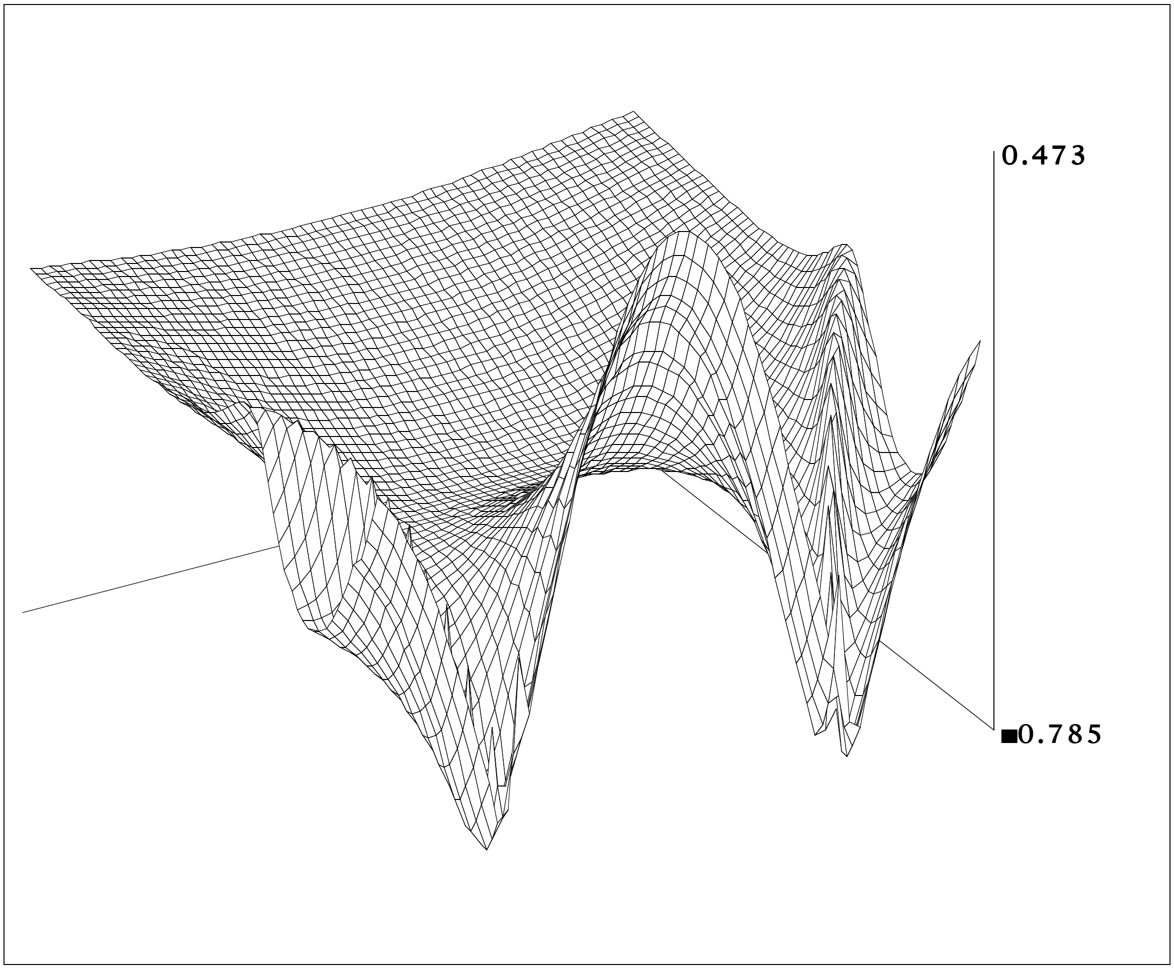


Ln_{er}

normalized electron density (log),
view from cathode

$$n_0 = 3.089 \cdot 10^{14}$$

normalization density, m^-3

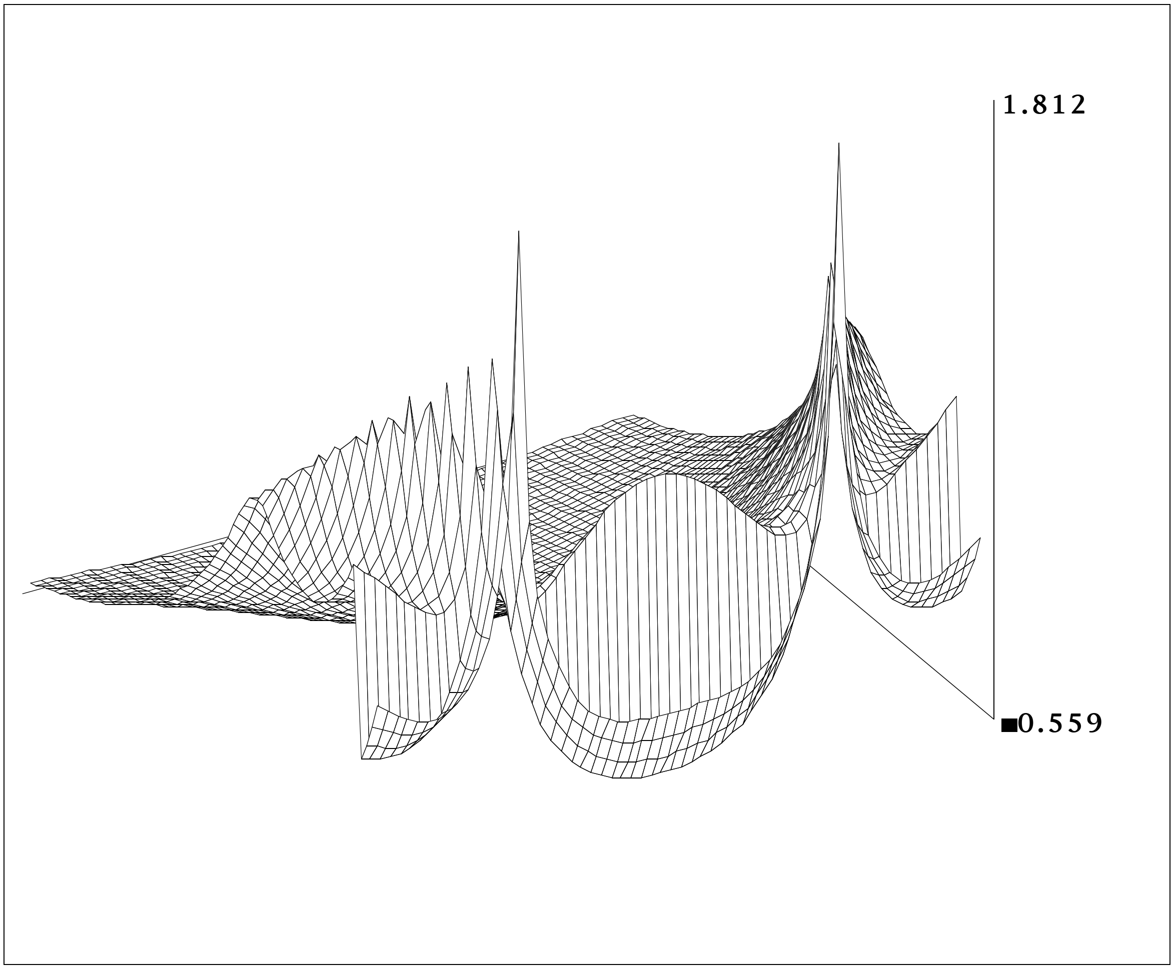


Lj_{yr}

normalized conduction current density (log),
view from cathode

$$j_0 = 5.114$$

normalization current density, amps/m^2

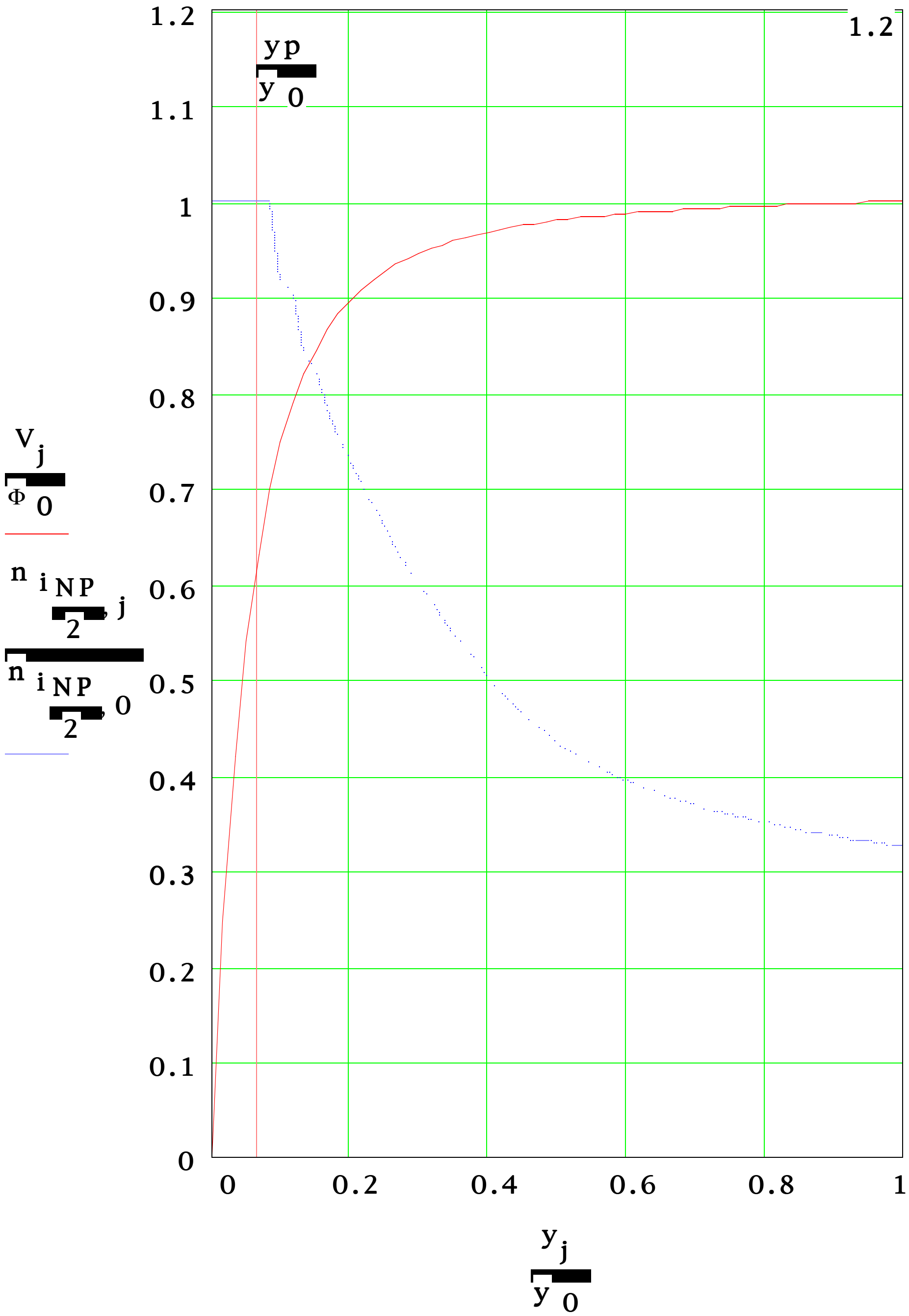


LQ_{er}

normalized electron power density (log),
view from cathode

$$Q_0 = 988.065$$

normalization power density, Watts/m^3



$y_0 \cdot 100 = 5.289$ cm

$\Phi_0 = 193.216$ volts

$n_0 \cdot 10^{-6} = 3.089 \cdot 10^{8}$ 1/cc

$n_{i_{\frac{NP}{2}},0} \cdot 10^{-6} = 9.8 \cdot 10^{8}$ 1/cc

$N = 1.062 \cdot 10^{15}$ 1/cc

$P = 30$ milli-torr, He

$\Phi_0 = 193.216$ volts

$I_M \cdot 10^3 = -8.556$ milli-amps (magnetron current)

$I_0 = 0.179$ amps per meter of magnetron z

$I_0 \cdot \Delta L \cdot 10^3 = 50.008$ total milli-amps, conduction current

$HX_{\frac{NP}{2},0} \cdot 10^4 = 519.999$ gauss @ surface

$y_0 \cdot 100 = 5.289$ cm (reach from cathode)

$j_0 \cdot 10^{-4+3} = 0.511$ milli-amps/cm*cm (conduction current)

$n_0 \cdot 10^{-6} = 3.089 \cdot 10^8$ 1/cc (exterior plasma)

$P_0 \cdot \Delta L = 9.662$ watts (for $\Delta L = 0.28$ meters)

$2 \cdot x_p \cdot 100 = 1.746$ cm (pole-to-pole width)

$\alpha_0 = 3.052 \cdot 10^5$ ionization rate, 1/sec.

$T_e = 7$ electron temperature, eV

$yp \cdot 1000 = 3.526$ mm, ion sheath = dark space